2008

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GEOLOGICAL NOTES

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ABSTRACT

At the Wave, a photogenic landform on the Utah–Arizona border, modern, southwesterly, sand-carrying winds abrade the Navajo Sandstone. Abundant trains of centimeter-scale, transverse, upwind-facing treads and risers cut sedimentary structures at a high angle. Central to the formation of these erosional steps are crusts produced by microbes lying just beneath exposed sandstone surfaces. Treads and risers are present on the walls of smoothly curved troughs at the Wave, on the walls of nearby circular scour pits, and on bedrock domes found at the center of scour pits. Because of their locations and orientations, the large-scale troughs and scour pits could not have been formed by flowing water or groundwater sapping; treads and risers indicate sculpting by the wind.

Introduction

Slickrock—naked eolian sandstone—is widespread in the canyonlands of southern Utah and northern Arizona. Since the early exploration reports by Powell (1873, 1895) and Dutton (1882), the Colorado Plateau has become renowned for its vivid displays of fluvial erosion. With only a few exceptions, the role of the wind in sculpting the region's landforms has received little attention. Here we show that a steplike topography with flat treads and centimeter-high, upwind-facing risers is present on Navajo Sandstone outcrops at and near the Wave, a photogenic landform astride the Utah–Arizona border. The small, steplike structures, in combination with the general lack of aqueous erosional features in smooth Navajo Sandstone exposures, demonstrate that the Wave and several other nearby large-scale landforms were (and continue to be) sculpted by wind.

Photosynthetic, endolithic microbes (Bell et al. 1986; Bell 1993; Souza-Egipsy et al. 2004) live a few millimeters below the surfaces of nearly all of the exposed sandstones in the study area and are integral to the formation of the treads and risers. The flat treads between the steep risers have underlying microbes, but the heavily abraded risers do not.

The purposes of this note are (1) to describe and interpret the abundant small-scale erosional treads and risers on the sandstone of the study area and (2) to use the treads and risers to better understand the origin of the larger landforms on which they are cut.

Study Area

The study area lies along the East Kaibab Monocline, in the northwest corner of Vermilion Cliffs National Monument, near the Utah–Arizona border. Here, the Navajo Sandstone is fine to medium grained, highly porous, weakly cemented, and about 600 m thick. Outcrops of the Navajo at the Wave (fig. 1; lat 36°59′753N, long 112°00′373W) provide unparalleled opportunities for detailed studies of Lower Jurassic primary sedimentary

Manuscript received March 26, 2007; accepted December 20, 2007.

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[The Journal of Geology, 2008, volume 116, p. 173–183] 0022-1376/2008/11602-0005$15.00. DOI: 10.1086/528902

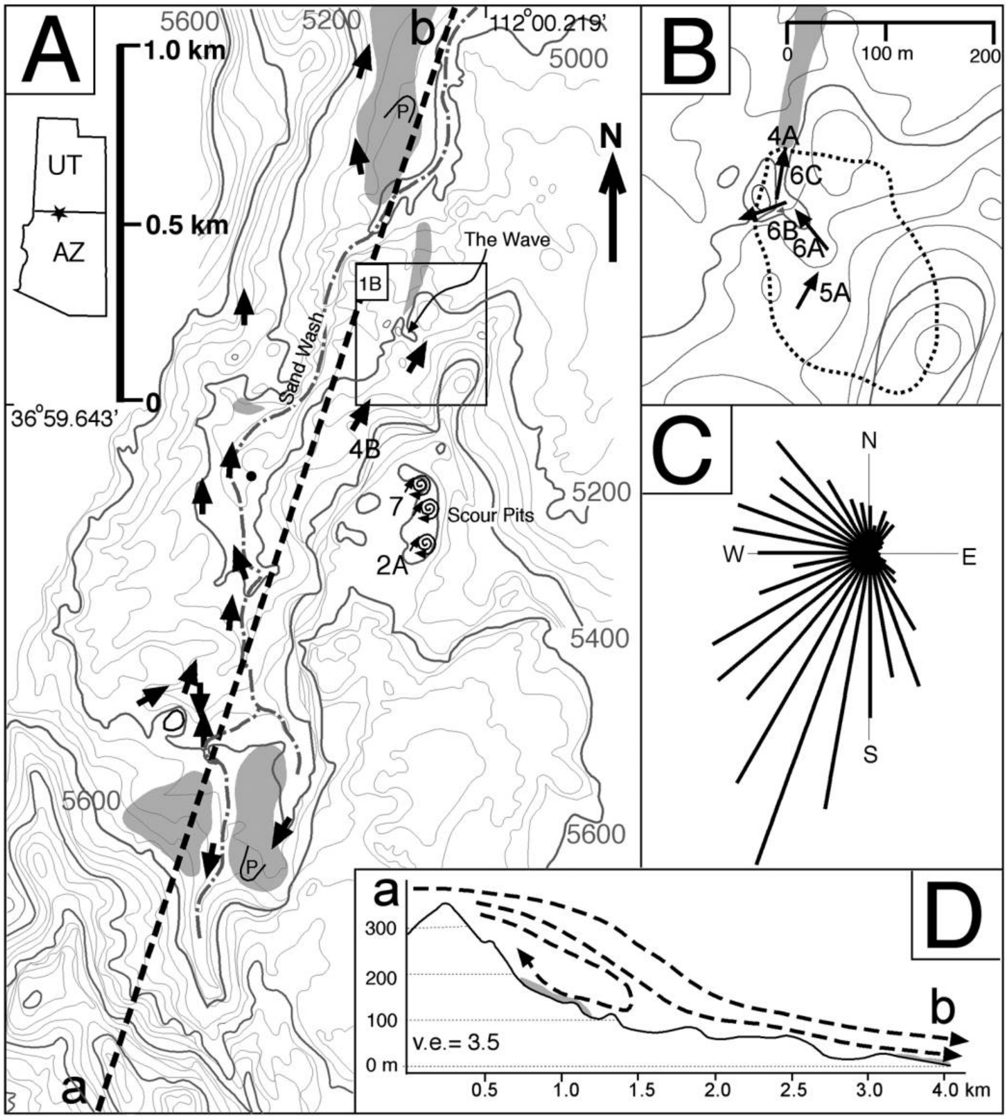

Figure 1. Locations of wind-eroded features, sand rose, and cross-sectional view of wind flow. *A*, Study area map. Arrows show locations of abundant small-scale erosional bedforms and their indicated wind directions. Numbered letters show locations of features shown in figures. Dot southwest of *4B* shows location of narrow trough described in text. Shading indicates areas of modern dunes; hooked lines show orientation of the crests of parabolic dunes (*P*); swirl patterns show locations of scour pits. Elevations of contours are in feet above sea level; coordinates use WGS84 data. *B*, Detailed map of the Wave, showing rainfall catchment area (*dotted line*), wind directions (*arrows*, based on erosional features), and locations of figures. *C*, Sand rose for Page, Arizona (1979–2005), computed by the Fryberger (1979) method. Page is 50 km ESE of the Wave. Lines extend in the directions from which sand-moving winds blow; lengths are proportional to the volume of sand moved. *D*, Cross-sectional view along *a*–*b* in figure 1*A*. Large eddy (due to separation of flow at the steep headwall of Sand Cove) moves sand in this small area southward, building dunes and cutting north-facing, centimeter-scale risers on sandstone surfaces. *v.e.* = vertical exaggeration.

structures and trace fossils, including climatically driven cyclic eolian stratification and a high density of well-preserved dinosaur tracks (Loope et al. 2001; Loope and Rowe 2003; Loope 2006). The sedimentological detail visible in these outcrops is at least partially due to the paucity of rock-encrusting lichens and vegetation. Small trees (*Juniperus osteosperma* and *Pinus edulis*) and shrubs (*Cowania*, *Arctostaphylos*, and *Cercocarpus*) occupy sites where their roots have access to joints in the sandstone or to the small accumulations of dune sand that are common in the study area (fig. 1). Winds of the region are strong and persistent; sand-moving winds are dominantly from the southwest (Hack 1941; fig. 1*C*).

In the study area, the Navajo Sandstone is composed of large-scale cross strata that have well-developed depositional cycles of alternating packages of grain-flow and wind-ripple strata (Hunter and Rubin 1983; Chan and Archer 1999; Loope et al. 2001). Wind-ripple strata weather in positive relief, as compared to the coarser-grained, better-sorted, and more friable grain-flow strata. Millimeter-scale pinstripes composed of fine to very fine sand define individual medium-sand grain-flow strata from a few centimeters up to 10 cm thick (Loope 2006). Wind-ripple strata are inversely graded and range in grain size from very fine to medium sand. The dip of grain-flow strata is 24°–25°, indicating that they have been compacted by about 28%. The degree of cementation in Navajo grain-flow strata is highly variable; in thin section, intergranular space (cement + porosity) averages 32% (Corey et al. 2005). In the study area, grain-flow strata are very lightly cemented, and porosity accounts for nearly all intergranular space.

The sandstone in the study area is jointed on several scales. Few joints appear to penetrate the entire thickness of the Navajo Sandstone. The most prominent set of tectonic joints visible on color-infrared digital orthophotoquads has orientations that range from 50° N to 69° E, with a secondary set trending approximately N 25°–15° W.

Small-Scale Erosional Bedforms

Description. Many of the Navajo Sandstone outcrops in the study display a stepped topography: flat treads alternate with steep, transverse, centimeter-scale risers (fig. 2). Individual risers are irregular in plan view and commonly extend several meters laterally. Fields comprising hundreds of treads and risers can cover hundreds to thousands of square meters. Within these fields, all risers face the same direction. Nearly all of the risers that are broadly exposed face south or southwest. The facing directions of risers do not bear a consistent relationship to the direction of local drainage, and some risers are present beneath overhangs that preclude their exposure to raindrop impacts. The faces of many risers are concave and loose; windblown sand is commonly present in these concavities (fig. 2*A*). Within a single field, the mean height of the risers can be as low as 2.5 mm and as high as 18 mm. Mean spacing ranges from 6 to 36 cm (fig. 3). Higher risers have wider intervening treads (fig. 4). Risers do not expose individual depositional laminae but instead nearly always cut the rock at a high angle to bedding (fig. 4). Treads and risers are most common on surfaces sloping <30°, but they are also present on some near-vertical surfaces, where they are aligned nearly perpendicular to topographic contours (fig. 5). Risers are present on both wind-ripple strata and grain-flow strata. Within depositional cycles of wind-ripple and grain-flow strata, however, the risers are much better developed on the grain-flow strata, whereas bundles of wind-ripple strata stand in positive relief above the grain-flow strata and display fewer, more poorly formed risers.

Fresh sandstone is exposed along the risers, but treads between risers are darkened. The dark treads between risers are typically unconnected—each successive pair of risers delineates a distinct darkened zone. Encrusting lichens are rare on treads. When this rock is wet and broken, a green layer of photosynthetic microbes is visible a few sand grains below the surface (Konhauser 2007, p. 196). Over most of the study area, the risers consistently face southward (toward the dominant southerly to southwesterly winds; fig. 1*C*). Knoblike ventifacts (fig. 6*A*) also indicate dominant flow from the south. In the southern part of the study area, however, risers on the floor of the canyon just below the headwall of Sand Wash face northward (fig. 1*A*).

Interpretation. The locations and morphology of the treads and risers demonstrate that these features are erosional bedforms cut by sand-laden winds. Wind-eroded features that are larger than ventifacts but smaller than yardangs have received relatively little attention (see review by Breed et al. [1997]). Allen (1984, p. 523) suggested that wind-abraded rocks could develop features similar in form and scale to the erosional forms cut into snow and ice (fig. 6*B*). Kurtz and Netoff (2001) showed that in arid, wind-swept settings in south-central Utah, endolithic microbes growing within friable Navajo Sandstone form durable surface crusts that retard erosion of host rocks. They demonstrated that under intense sandblasting, some rocks displayed small, undercut flutes that point into the wind. They noted that rock surfaces with flutes were always inhabited by microorganisms; erosional flutes did not form on rock surfaces lacking microbial crusts. Flutes similar to those described by Kurtz and Netoff (2001) are present at the Wave but are much less abundant and less extensive than the transverse treads and risers.

Some erosional features developed on wind-abraded snow have the same form, height, and wavelength as do the bedforms developed on the

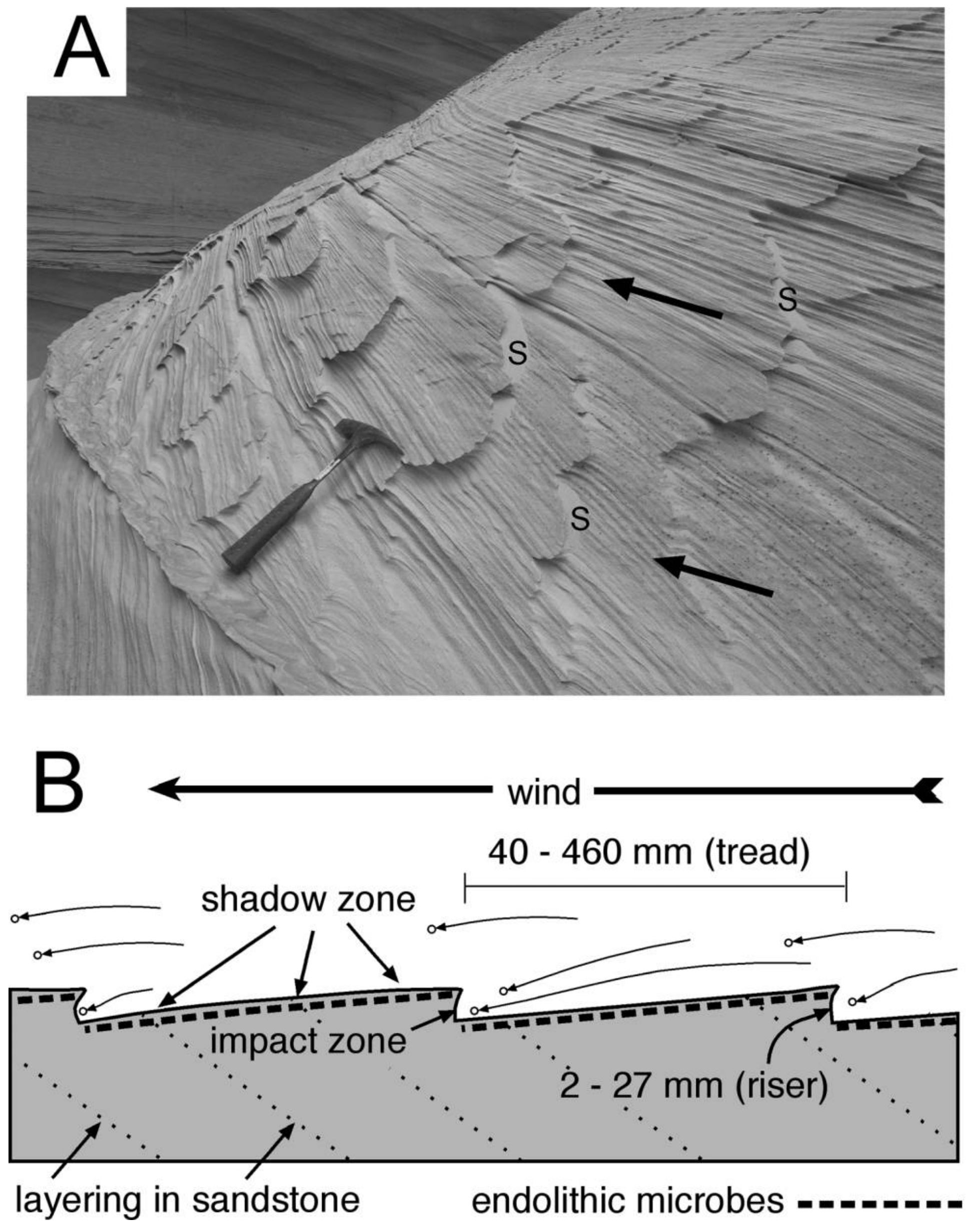

Figure 2. Characteristics of treads and risers cut into Navajo Sandstone. *A*, Upwind-facing, overhanging risers (up to 27 mm high) on sloping sandstone surface. Note loose sand (*S*) beneath overhangs. *B*, Schematic showing treads, risers, and microbial colonies migrating to the left (downwind). Differential erosion is controlled by binding action of microbes, not by rock structure.

surface of the Navajo Sandstone (fig. 6*B*). All the erosional features we have observed in snow, however, are developed in stratified drifts, and unlike our Navajo Sandstone examples, the laminated character of the snow deposit directly controls the heights of snow risers. In both cases, the formation of risers is apparently dependent on the differential erodibility of layers within the substrate. In the case of the Navajo Sandstone, where risers cut across laminations in the sandstone, differential erodibility is provided by the binding action of the endolithic microbes (a single segmented layer; fig. 2*B*), not by the inherent structure of the deposit (multiple parallel layers).

Here we surmise that the treads and risers are, like eolian depositional bedforms (Anderson 1990), products of self-organization. Sharp (1963) argued that wind-ripple wavelength is controlled by the

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.75'	112°00.37'	14.8 cm	5.4	4.5 mm	1.3

λ	h	λ	h	λ	h	λ	h	λ	h
7	5	15	3	12	7	16	4	15	3
9	6	18	4	20	5	29	4	9	4
18	3	14	5	15	5	11	5	16	6
9	3	10	7	15	8	12	5	12	5
15	3	14	3	25	4	15	6	8	4
9	3	15	3	27	3	16	4	19	4
18	5	18	4	18	3	8	4		5

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.51'	112°00.68'	23.1 cm	10.9	7.0 mm	2.5

λ	h	λ	h	λ	h	λ	h	λ	h
22	4	20	10	20	6	39	10	4	8
24	6	17	10	14	6	37	10	14	5
20	5	23	7	5	3	43	14		3
22	6	10	7	42	9	38	6		5
18	7	22	7	34	9	23	7		
11	8	9	4	44	9	30	10		
23	10	20	5	10	7	23	45		

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.50'	112°00.68'	20.7 cm	6.9	8.8 mm	3.2

λ	h	λ	h	λ	h	λ	h	λ	h
28	6	18	7	19	8	27	12	20	8
21	4	27	8	18	10	30	14		7
7	4	11	7	17	13	30	13		
18	7	10	14	24	10	28	6		

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.24'	112°00.43	35.5 cm	11.9	18.1 mm	8.3

λ	h	λ	h	λ	h	λ	h	λ	h
71	15	38	22	33	20	15	16	33	
43	14	25	21	33	17	28	18	30	
30	16	30	27	46	21	41	10	36	

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
37°02.52'	111°59.32'	11.1 cm	3.2	8.2 mm	7.1

λ	h	λ	h	λ	h	λ	h	λ	h
10	10	11	8	8	5	12	17	14	
15	10	19	7	11	5	12		10	
14	7	7	6	11	8	8		13	
13	8	11	6	15	10	5		8	

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.53'	112°00.35'	10.1 cm	3.8	2.5 mm	0.5

λ	h	λ	h	λ	h	λ	h	λ	h
15	2	3	2	15	3	6	2	8	3
9	2	8	3	13	3	14	3	5	3
7	2	11	3	11	3	8	3	7	2
10	3	16	2	15	2	6	3		
11	2	11	2	15	2	7	3		
9	2	9	3	10	2	6	2		
8	3	13	2	20	3	7	2		

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.50'	112°00.70'	12.5 cm	3.6	9.0 mm	4.4

λ	h	λ	h	λ	h	λ	h	λ	h
7	7	23	9	13	11	13	12		7
14	8	13	6	13	4	13	13		8
14	5	11	8	9	12	10	9		
12	8	8	6	10	8		24		
14	6	14	15	10	3		14		
12	4	15	13	12	5		10		

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
36°59.51'	112°00.68'	16.6 cm	6.6	4.8 mm	1.3

λ	h	λ	h	λ	h	λ	h	λ	h
19	5	20	4	20	4	13	4	19	5
26	4	17	5	15	5	12	4		8
25	5	6	5	10	8	8	6		6
14	3	16	4	11	5	15	4		4
17	3	7	6	22	4	30	5		
25	3	16	4	13	5	26	5		
25	3	25	7	8	4	5	5		
14	5	23	3	15	4	12	6		

Lat. N	Long. W	X_λ	σ_λ	X_h	σ_h
37°02.52'	111°59.32'	12.3 cm	3.4	3.0 mm	0.5

λ	h	λ	h	λ	h	λ	h	λ	h
20	3	9	3	12	3	12	3	7	3
8	4	9	2	13	3	12	3	10	3
15	3	11	3	8	2	15	3	13	3
15	3	18	3	20	2	14	3	8	3
13	3	11	3	15	3	15	3		
9	3	7	4	15	4	9	3		
12	3	16	3	11	3	12	4		

Figure 3. Measurements of wavelength (λ) and height (h) of small-scale erosional bedforms from nine localities, with mean (X) and standard deviation (σ) values for each. GPS coordinates based on WGS84 data.

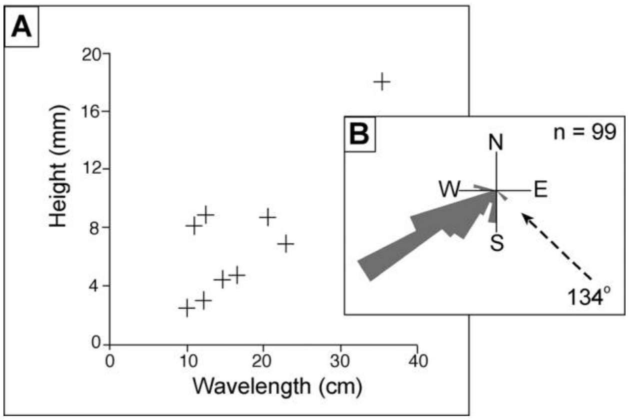

Figure 4. Dimensions of treads and risers. *A*, Each plus sign represents the mean height and spacing for 12–34 pairs of treads and risers from individual fields of erosional bedforms (fig. 3). *B*, Azimuths of risers at the Wave; mean = 225°; SD = 26.2°; interpreted direction of erosive winds = 134° (perpendicular to the trend of the transverse bedforms).

length of the zone shadowed from significant impacts in the lee of the ripple form and is therefore proportional to ripple height. In wind ripples, the ratio of wavelength to height (the ripple index) varies from 10 to 70 (Bagnold 1954). The analogous ratio for the treads and risers on Navajo outcrops (fig. 4) ranges from 14 to 41.

Although the risers occupy <5% of the sandstone surface, they receive most of the impacts of wind-borne grains, leaving the intervening treads nearly untouched. Because the flat portions of the rock surface lie in the shadows of the risers, they are suitable sites for microbial growth.

We interpret the north-facing risers near the head of Sand Wash as indicators that as strong southerly winds blow over the steep headwall of the canyon, flow separation takes place, and a lee eddy with northerly surface flow develops (fig. 1*D*). This interpretation is corroborated by the presence of southward-migrating parabolic dunes at the head of the canyon (fig. 1*A*). Gusts from such an eddy that moved dune sand were observed during the early afternoon of December 11, 2006. Winds within lee eddies are typically weaker than the main (separated) flow (Oke 1987, p. 184). The treads and risers near the head of Sand Wash that were apparently developed by the winds of the lee eddy suggest that formation of treads and risers in the Navajo Sandstone does not require especially high wind velocities when other conditions are favorable.

Treads and risers high on near-vertical rock faces (fig. 5) show that scour is not restricted to low-lying rock surfaces. Bagnold (1954) showed that during saltation of sand over dune surfaces, grains are ejected from the substrate by high-energy impacts

Figure 5. Treads and risers (*arrows*) on steep sandstone surfaces; locations of photos shown in figure 1. *A*, Winds descend from the adjacent plateau and pass through the trough of the Wave, where they scour sandstone surfaces 5 m above the floor of the trough. *B*, Escarpment and observer under attack by sand entrained by strong southwesterly winds. Treads and risers (*arrows*; bright lines in lower part of photo, dark lines in upper part) are perpendicular to flow.

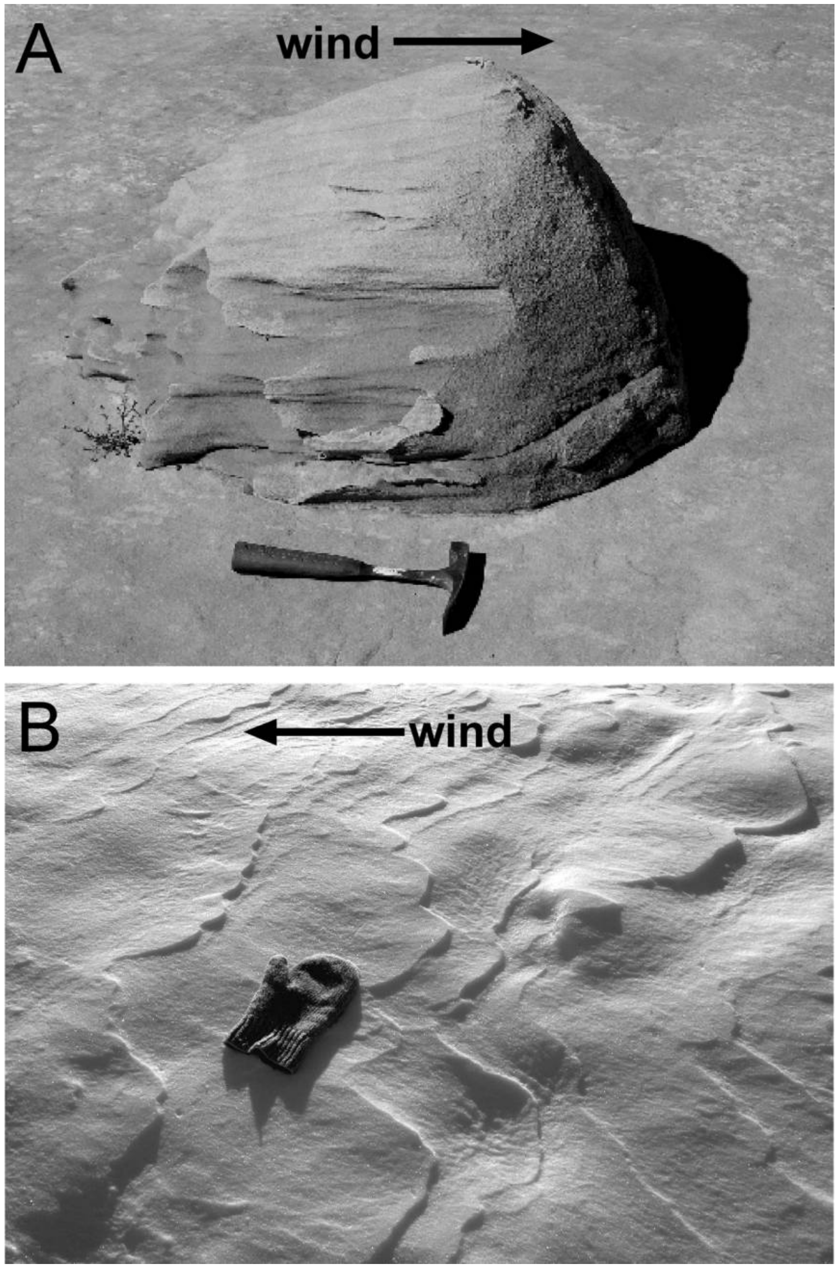

Figure 6. *A*, Ventifact developed on bedrock knob that is 10 m above and 100 m south (upwind) of the Wave (see fig. 1*B* for location). Sand-bearing southwesterly winds blow left to right. *B*, Wind-eroded forms cut into snow are similar in form and scale to the treads and risers developed on Navajo Sandstone outcrops at the Wave. Note, however, that each riser is developed on a distinct depositional lamina; depositional laminae do not control the position of the sandstone risers (cf. fig. 2*B*). Mitten is 25 cm long.

and return to that surface by gravity; grains rarely rise higher than a few tens of centimeters above the dune surface because energy is lost as grains splash into soft sand. Saltating grains can reach heights >3 m if they rebound from hard substrates (Pye and Tsoar 1990, p. 107). Because of the high local relief of the sandstone surfaces at the Wave, however, the presence of treads and risers on the high, nearly vertical rock surfaces does not require extreme rebound heights of saltating grains. Instead, energetic impacts take place as sand-bearing winds move down and through the main trough at the Wave, transporting sand from rock surfaces at higher elevations just to the south (fig. 1). The im-

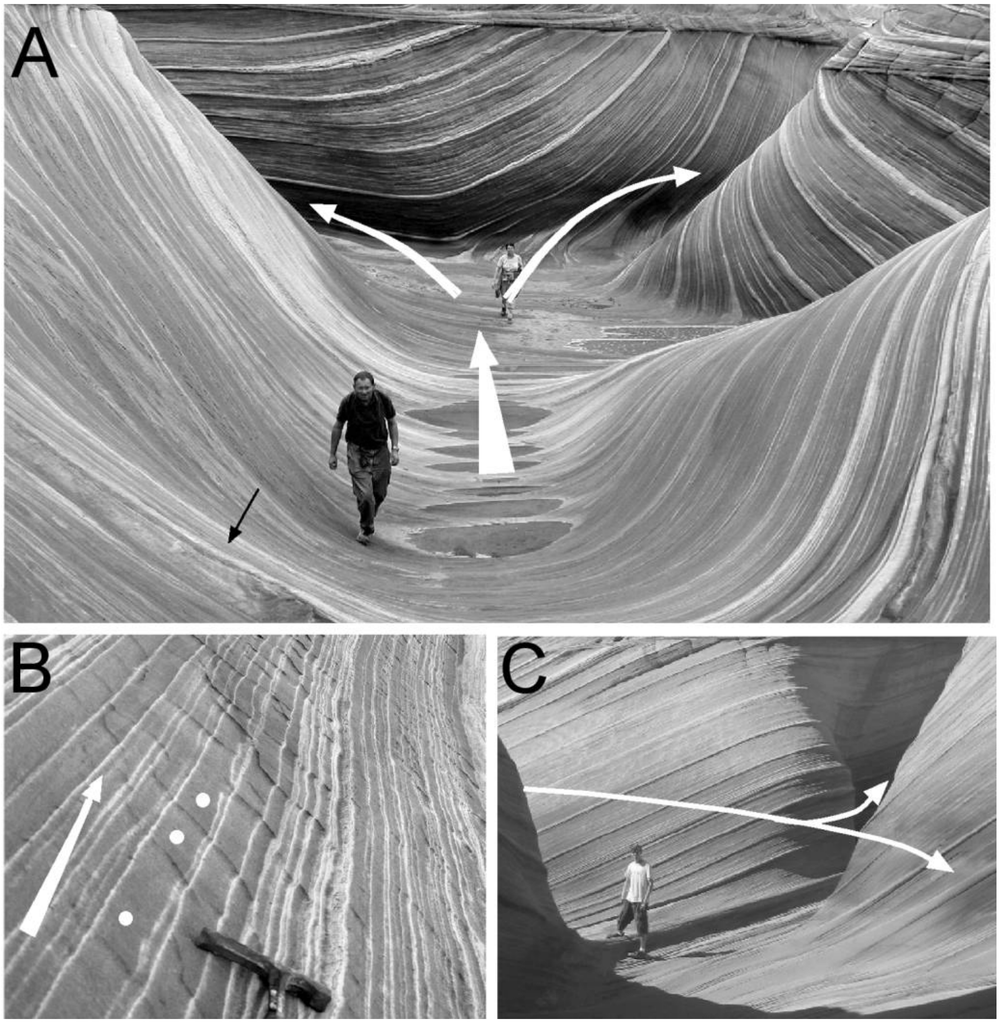

Figure 7. Large-scale erosion features at the Wave. Arrows show direction of erosive winds. See figure 1 for locations. *A*, Intersection of smoothly curving erosional troughs at the Wave. *B*, Treads and risers from arrowed location in *A*. Risers (about 1 cm high) face into the wind. Dots mark distinct zones of microbially darkened sandstone of treads separated by clean sandstone of risers (darkened by shadow). *C*, Trough intersection at the Wave (at right angle to view in *A*). Note that wind-ripple strata have weathered into positive relief. Man's right foot is atop a threshold that crosses the main trough. These features are evidence against trough cutting by fluvial action.

pacts of the grains on the near-vertical surfaces cannot be attributed to the gravitational force acting on saltating grains, as evidenced by riser orientation; the treads and risers on these surfaces likely result from grains being cast laterally against the walls as strong winds are abruptly deflected during their passage through the troughs.

Formation of the erosional treads and risers requires (1) conditions favorable for the growth of microbes (to form a crust) and (2) wind-borne sand that strikes the sandstone surface with high energy and at a low angle (to cut the risers). Erosional treads and risers are not ubiquitous on the slickrock; some fresh sandstone outcrops are exposed to a strong flux of sand and do not develop risers. This absence may be because sandblasting is occurring at a rate that exceeds the rate of microbial colonization and growth. The slope and aspect of the surface, which influence the availability of water to endolithic microbes, also play important ecological roles in this interaction.

Large-Scale Landforms

Two types of large-scale landforms within the study area—scour pits and troughs—have distinctive features that suggest an eolian origin. Transverse centimeter-scale risers are well developed on the walls of both of these features (figs. 2*A*, 7*B*).

Eolian Scour Pits. *Description.* Three scour pits are present on the plateau directly upslope from the Wave (fig. 1). They are circular in plan and 15–55 m in diameter, and they occupy indentations in cliff faces (fig. 8*A*). Vertical to overhanging walls up to 20 m high form at least 180° of their perimeter. Along the perimeters of the two largest scour pits, scour pit floors are downcut (countersunk) as much as 4 m below the lowest points on the walls. Bedrock domes occupy scour pit centers. The dome in the largest scour pit is nearly completely covered by a large sand dune (fig. 8*B*). Scour pit walls also display smooth, near-horizontal, bifurcating scours up to a meter in diameter (fig. 8*C*). A small volume of water drips off walls, flows onto the floor of scour pits during rain storms, and accumulates in shallow, closed depressions. Wind enters and circulates as a vortex within the scour pits.

Interpretation. The scour pits are products of ongoing wind abrasion. Water plays no role in the scouring process. The watershed of the scour pits cannot supply sufficient water or energy for water-driven erosion. Bedrock weathering is not preferentially occurring in areas where water stands.

All three scour pits formed along an irregular rock scarp that lies just upwind of a large north-facing cliff (fig. 1*A*). Windblown sand often accumulates along cliff faces. Echo dunes, for example, are deposited on the upflow side of cliffs in the zone of flow separation by an eddy with a horizontal axis (Tsoar 1983). The circular, countersunk scour pits in our study area, however, were scoured by vortices with vertical axes. Our working hypothesis is that such vortices were localized along the steep, irregular cliff when strong southerly to southwesterly winds moved over high points and through gaps in the cliff (Oke 1987, p. 185). Winds within these vortices undercut the sandstone walls of each scour pit, deepening the scour pit floor only around its perimeter while leaving a high, central bedrock dome. Sand entering the scour pit became trapped

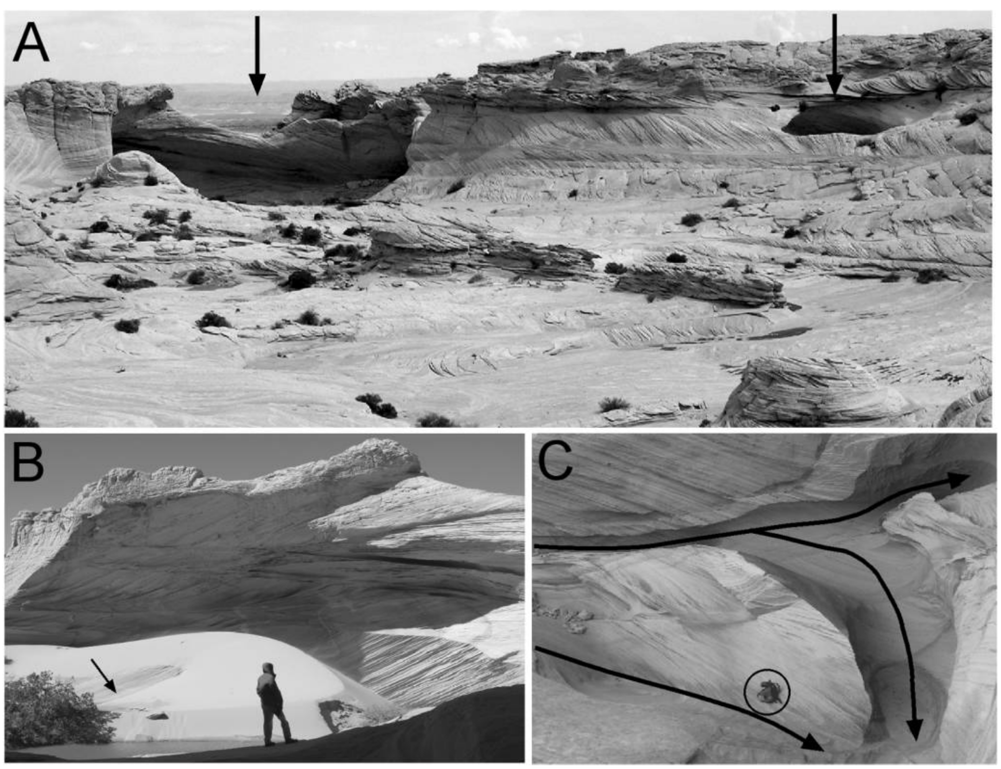

Figure 8. *A*, Two adjacent, wind-eroded scour pits; view looks northeastward (downwind). Scour pits are positioned on mesa top and have tiny water catchments, suggesting that fluvial action and groundwater sapping contributed almost nothing to their formation. Scour pit on left is about 55 m in diameter; shrubs in foreground are about 1 m high. *B*, Scour pit shown on left side in *A*. Note sand dune in center of structure. Arrow points to small exposure of a central bedrock dome nearly completely covered by dune sand. *C*, View of strongly fluted southern wall of wind-scoured scour pit (behind person in *B*). Day pack (*circle*) for scale.

within it, assuring the availability of impactors for the abrasion process.

Although they are present on the bedrock domes and most scour pit walls, the small, steplike bedforms are absent from the bifurcating scours (fig. 8*C*). The scour events may be too severe and too frequent to allow microbes to develop the skin necessary for differential erosion.

Wind-Scoured Troughs. *Description.* At the Wave, two large troughlike scours meet to form a roughly north-south-trending feature approximately 96 m in length (fig. 1*B*). The walls of the broader trough (fig. 7*A*, *foreground*) form a smooth, U-shaped arc reaching a maximum width of 19 m. The narrower trough (fig. 7*C*) separates two buttes and is only 16 m long; it abruptly ends westward where the contours of the buttes diverge. Large knob-shaped ventifacts formed by strong southwesterly winds are present on the small plateau that lies 10 m above and 50 m south of the trough (fig. 6*A*). A deposit of dune sand stretches from immediately north of the Wave to Sand Wash (fig. 1). No joints are visible on the floors of these troughs. Tabular bundles of wind-ripple laminae averaging 5.7 cm thick on the walls and floors of these troughs weather in positive relief. On trough floors, they form prominent thresholds, or steps, protruding an average of 5 cm from the trough base, with a maximum threshold height of 45 cm (fig. 7*C*). Within a narrower trough that separates two buttes southwest of the Wave (fig. 1*A*, *dot*), a threshold composed of erosion-resistant wind-ripple laminae is higher, thinner, and more delicate than the thresholds at the Wave.

Heavy rains leave pools of water that stand in the low points of the broader trough of the Wave (fig. 7*A*). The rainfall catchment area for this trough is about 0.05 km^2 (fig. 1*B*); the catchment for the smaller trough (fig. 7*C*) is even smaller, perhaps several hundred square meters. On October 5–14, 2006, southern Utah and northern Arizona received about 150 mm of rainfall—a rare occurrence in an area where the annual mean precipitation is <250 mm. Runoff from this precipitation created a 1.0-m-deep pool in the large trough; overflow from the pool entered an area of dune sand that lies directly north of the Wave (fig. 1*B*). On October 16, very little sediment was present on the bedrock floor of the pool.

Interpretation. Three phenomena show that sand-laden winds are actively abrading the walls of the troughs: (1) small-scale erosional bedforms with clean, upwind-facing risers in the Wave (fig. 7*B*); (2) knob-shaped ventifacts immediately upwind (fig. 6*A*); and (3) an accumulation of dune sand immediately downwind (fig. 1). The Wave constricts in its middle portion and acts as a natural venturi, increasing the wind's velocity through this central passage. Because of flow expansion, the wind then slows abruptly at the north end of the trough and drops its load of sand. The presence of dune sand at this site attests to the volume of impactors that abraded the trough as they passed through the Wave.

The tiny catchment areas for the troughs and the integrity of the thresholds occupying the axes of the troughs negate the possibility that sediment-laden floods scoured the troughs. The thresholds occupy the positions within the troughs most vulnerable to scour during flooding. The paucity of sediment in the main trough on the floor of the pool immediately after the major October flood event suggests that runoff has little erosive power at this site. Additionally, the troughs lack water-cut chutes and pools similar to those carved into Navajo Sandstone along Sand Wash, where water regularly flows during storm events. The smooth cross-sectional profile of the large trough (fig. 7*A*) indicates that abrasion is taking place around the full perimeter of the trough and not just in the part that is subject to flooding, corroborating the view that floods play an insignificant role in trough formation.

Troughs may have been initiated by weathering along vertical joints, but no direct evidence remains of this phase of landform development. Flowing water could also have been important at an earlier time, but the evolution of the landscape effectively truncated the watershed above the Wave to the point that there is insufficient flow to drive contemporary erosion. Joints that were favorably oriented may have been slowly enlarged by sand-bearing winds flowing through narrow passages between buttes. Because the floors of present-day troughs lack joints, appreciable downcutting has taken place following an initial joint-controlled phase.

Conclusions

The Jurassic Navajo Sandstone exhibits small, self-organized, wind-erosion bedforms that are significant to understanding landscape development on the Colorado Plateau. An important feedback mechanism with endolithic microbes has potential application to understanding microbial interactions with host rock on Earth as well as on other planets (Squyres and Knoll 2005). Specific characteristics and implications of this study are as follows. (1) Abrasion of friable sandstone outcrops can generate transverse, centimeter-scale erosional bedforms with steep risers that face into the wind. These bedforms appear to form only when endolithic microbes generate a skin that can be undermined. (2) Smoothly curved sandstone troughs that intersect at the Wave are decorated with abundant wind-erosional bedforms. The troughs were generated by wind erosion and are being actively eroded today. (3) Where strong winds move over irregular sandstone cliffs, vertical vortices can scour deep pits with overhanging walls and central bedrock domes that are prone to burial by dune sand.

ACKNOWLEDGMENTS

We thank R. Schmeisser for help with the wind data from Page, Arizona. We also appreciate the help and encouragement from D. Powell (Escalante–Grand Staircase National Monument), R. Cox (Bureau of Land Management, Arizona Strip Field Office), and M. Salamacha (Bureau of Land Management, Kanab Field Office). Fieldwork was funded by the National Science Foundation (grant EAR02-07893 to D. B. Loope) and by the National Aeronautics and Space Administration (grant NNG06GI10G to M. A. Chan, issued through the Mars Fundamental Research Program).

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